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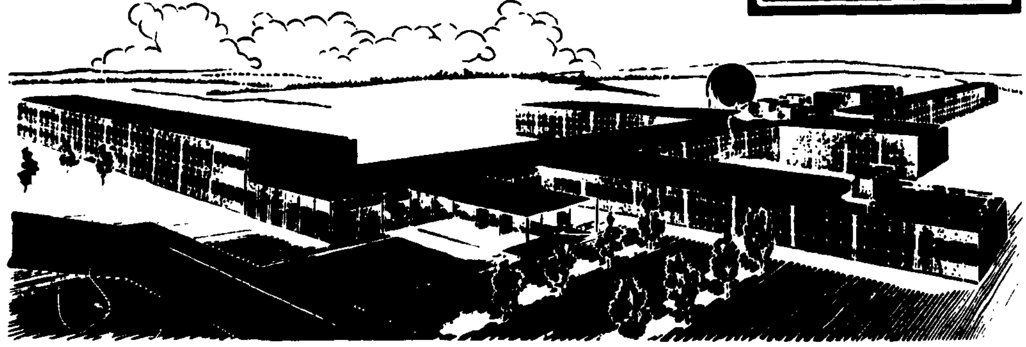
RELIABLE SPARK GAP FOR CAPACITOR BANK SWITCHING

W. D. BUNTING, JR.
PLASMA PHYSICS RESEARCH LABORATORY

NOVEMBER 1963

AEROSPACE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE



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Project 7073
Task 7073-01

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WRIGHT-PATTERSON AIR FORCE BASE, OHIO

FOREWORD

This technical report was prepared by Lt. W. D. Bunting of the Plasma Physics Research Laboratory of the Aerospace Research Laboratories, Office of Aerospace Research, United States Air Force. The work reported was supervised by Mr. P. Bletzinger of the same Laboratory and was accomplished on Task 7073-01, High Energy Plasma Generation and Control under Project 7073, Research on Plasma Dynamics.

ABSTRACT

Hold off reliability, switching time, and jitter are measured for a newly designed spark gap switch to be used in a 3 kilojoule capacitor bank. Time study photographs of the breakdown are used to explain the existence of two distinct modes of switch operation depending upon a critical value of the working voltage.

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INTRODUCTION

The device used most often for switching high energies in short times from a capacitor bank is the spark gap switch[1, 2]. The most common design for a spark gap has been the three electrode version, incorporating an anode, cathode, and triggering electrode. Although this type of switch has been used for several years, there is much to be investigated before the breakdown mechanism is understood. In order to gain a better understanding of this mechanism and to measure the general characteristics of the particular spark gaps designed for triggering a 6 capacitor, 3 kilojoule capacitor bank, an investigation is being made of one of the gaps. This initial investigation has included the measurements of hold off reliability, switching time, jitter, and inductance. In addition, a Kerr cell shutter has been used to make time study photographs of the breakdown. These time studies have been used to further prove the explanation made by Lupton[3] for the existence of two distinct modes of operation depending upon a critical value of the working voltage.

DISCUSSION

Spark Gap Design

In designing a spark gap switch the following objectives must be considered. The switch should have low inductance so that the inductance of the pulsing system is small and high current rates can be achieved. The switch must be able to withstand the electromagnetic forces of the high current discharge in the megamp region. Since electrode erosion limits the switch lifetime, the best suited electrode material must be selected, and also considered should be a design which incorporates a method to force the spark away from

the initial breakdown point during most of the discharge. Other aspects are acoustical noise, atmospheric conditions, dust, and ease of maintenance. Attempting to consolidate these objectives into one design and yet keep the cost low, the switch shown in Fig. 1 was the result.

Breakdown Voltage Stability

The first requirement for a useable spark gap switch is predictability of the breakdown voltage for a particular gap width. There is no exact voltage at which the gap sparks, but for a well designed gap the range of breakdown voltages for a particular gap width will be small. A narrow range is desirable since the voltage can then be safely set close to breakdown value with small chance of a spontaneous breakdown. This range of values was measured for several different gap widths by slowly charging a capacitor in parallel with the gap and measuring the voltage at breakdown on an accurate electrostatic voltmeter. Over a hundred readings were taken for each gap setting and the range was found to be within plus 1 percent and minus 3 percent of the average breakdown value. A plot of average breakdown voltage versus gap width is shown in Fig. 2. After several thousand firings the gap width was set at several arbitrary values and the breakdown voltage was still predicted accurately by the curve.

Switch Closing Time

For an ideal switch the rate of change of current is maximum the instant the switch is closed. If one measures the voltage across an inductor in series with the gap, the time at which the switch first closes can be measured, since the voltage across an inductor is proportional to the rate of change of current, i.e., $V_L = -L \frac{dI}{dt}$.

The basic circuit used for most of the measurements is that of Fig. 3. Modifications of this circuit were made for each particular type of measurement. The inductor used for voltage measurements is a straight piece of No. 12 copper wire of inductance less than 0.1 microhenry. The voltage across the inductor was monitored with a Tektronix Model 507 oscilloscope. Fig 4 is a typical oscillogram of the voltage across the inductor upon spontaneous breakdown. It can be seen from the rise time of the pulse that the switch closes in less than 10 nanoseconds. However, this value cannot be measured accurately with the 507 oscilloscope since the rise time of the oscilloscope is 10 ns. One should notice the small hump preceding the main pulse. Photographs (Fig 5) of the spontaneous breakdown show that the spark forms between the anode and the trigger electrode and then forms across the surface of the insulation to the cathode. The small hump in Fig 4 indicates the initial breakdown to the trigger pin which precedes the breakdown between cathode and anode. When the trigger pin was shorted to the cathode no initial hump was observed. Except for an occasional breakdown to the edge of the insulation hole in the cathode, the gap broke down to the trigger pin for all gap widths measured.

Switching Time and Jitter

Of most importance when using spark gap switches in parallel is the time interval from trigger to breakdown and the variation of this interval from pulse to pulse called jitter. Separate measurements were made to record the time at which the trigger pulse occurred. The time interval from trigger pulse to closing of main gap was defined as the switching time. The trigger pulse was produced by a method described by Theophanis[4] and had a negative amplitude of

30 kilovolts with a rise time of approximately 10 nanoseconds. It is important that the trigger pulse be negative so that the gap is actually over-volted. The reasoning for this will be given in the next section.

Fig 6 shows a typical oscillogram of a triggered discharge. The first large pulse indicates the closing between trigger pin and anode and occurs approximately 10 nanoseconds after the maximum of the trigger pulse. Of course, the accuracy of this time measurement may very well be limited by the rise time of the oscilloscope. The second voltage rise denotes the actual closing between anode and cathode and occurs about 40 nanoseconds after the trigger pulse. Fig 7 shows a typical record of the jitter. Ten pulses are recorded on the same film and the width of the trace defines the jitter. The jitter is seen to be less than 5 nanoseconds but since the trigger has a jitter of approximately this magnitude, the observed jitter of the spark breakdown may stem from the trigger.

Oscillograms were made for various gap voltages at a set gap width and both jitter and switching time remained constant until a lower limit of the working voltage was reached, where the jitter and switching time both increased rapidly with further lowering of the voltage. However, with changing gap width the switching time decreased as the gap was lengthened and higher sparking potentials used.

"Fast" and "Slow" Modes of Switching

Lupton[3] describes two distinct modes of switch operation, depending upon whether the initial trigger spark travels first from the trigger pin to the anode or across the surface of the insulation to the cathode. Since a definite potential, V_S, is required to cause breakdown across the surface of the teflon insulation, a

criterion can be set to define when the switching changes from the "fast" to the "slow" mode of operation. If the sum of the trigger voltage, V_T, and the working voltage, V, reaches the gap breakdown potential, V_B, before V_T attains the value V_S then the initial spark will jump from the trigger pin to the anode. This is called the "fast" mode, because switching time and jitter are small and remain constant as the working voltage is varied at a particular gap width. If V_T reaches the value V_S before $V_T + V$ reach the value V_B, the initial spark will jump from the trigger pin across the insulation to the cathode. This is called the "slow" mode since switching time and jitter increase rapidly as the working voltage is further lowered. This explains why the trigger pulse must necessarily be negative in order to attain the "fast" mode of operation.

Verification of the above explanation has been achieved by making time study photographs for both modes of operation. A Kerr cell designed by Electro-Optical Instruments, Inc., was used as a shutter to take 5 nanosecond exposures of the spark breakdown. Although only one exposure could be made for each breakdown, the sparks were sufficiently reproducible for a time sequence to be assembled by changing the delay time at which the shutter was opened for each spark. In this manner a series of photographs was taken for each mode of operation. Fig. 8 is a sequence for the "fast" mode. The cathode and trigger pin are on the left in each picture. The zero time is arbitrary and the time delays recorded serve to show the time delay between each of the exposures. These time delays have an uncertainty of approximately $\pm$ 10 nanaoseconds due to the combined jitter of the Kerr cell system and the spark gap breakdown. Thus a large number of exposures was required to obtain a reasonable sequence.

It should be noticed that a faint channel forms across the gap in the first picture followed by a brighter streamer in the following pictures. It should of course be observed that the spark jumps first to the anode before a breakdown is observed from trigger to cathode. Fig. 9 shows a sequence for the "slow" mode of operation and, in agreement with Lupton, the initial spark is across the surface of the insulation.

It should be mentioned that the potential required to cause breakdown across the teflon insulation is on the order of 6 kilovolts. The switch can therefore be operated well below the static breakdown voltage, V_B, and still switch by the "fast" mode. Thus, the switch is safe from a spontaneous misfire without sacrificing reliability or switching speed during triggered operation.

Conclusions

The data for stability, switching time, jitter, and lifetime compare favorably with published data for other similar spark gaps. Only the inductance, measured to be approximately 0.15 microhenry, is comparatively high. But since the load for the capacitor bank will probably be on the order of 0.5 microhenry and since six switches will be used in parallel, the total inductance will still be low compared to that of the load. In conclusion, the described switch will be adequate for the purpose for which it was designed and with some modifications for lowering of inductance could be used in even more demanding capacitor bank systems.

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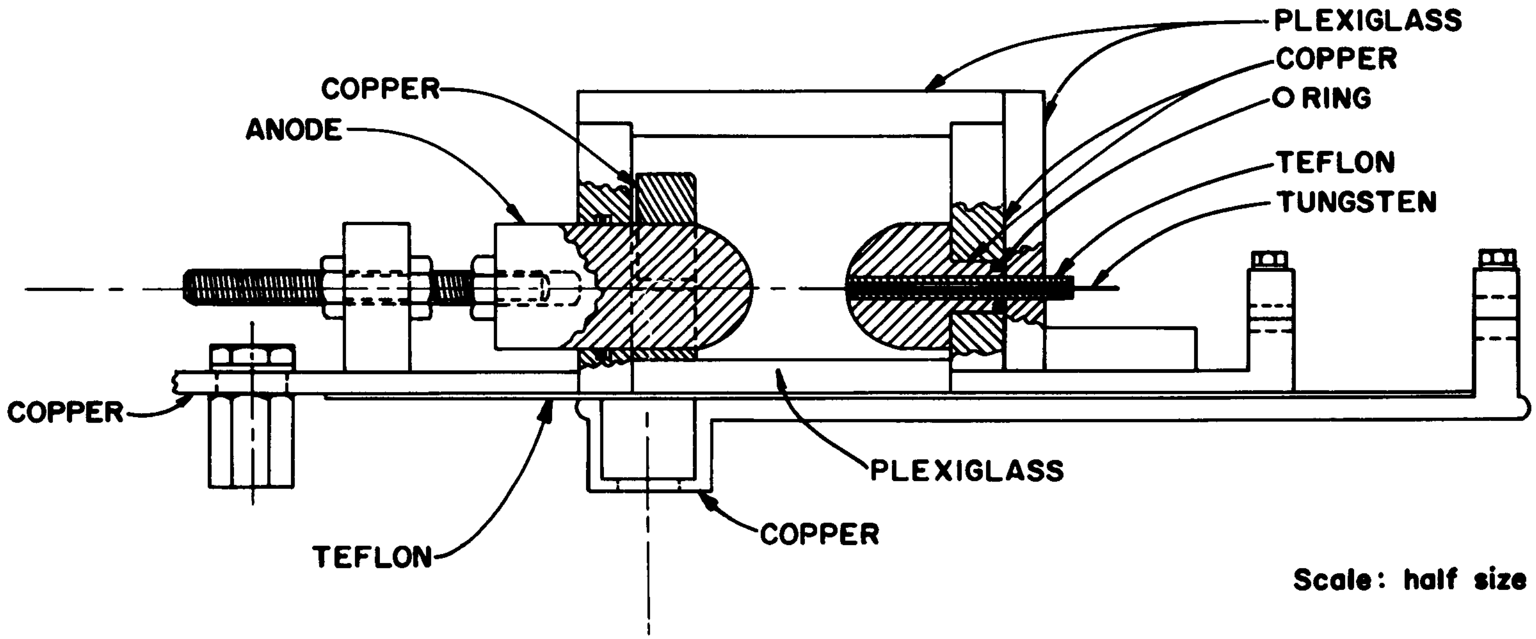

FIGURE I. ASSEMBLY DRAWING OF THE SPARK GAP SWITCH

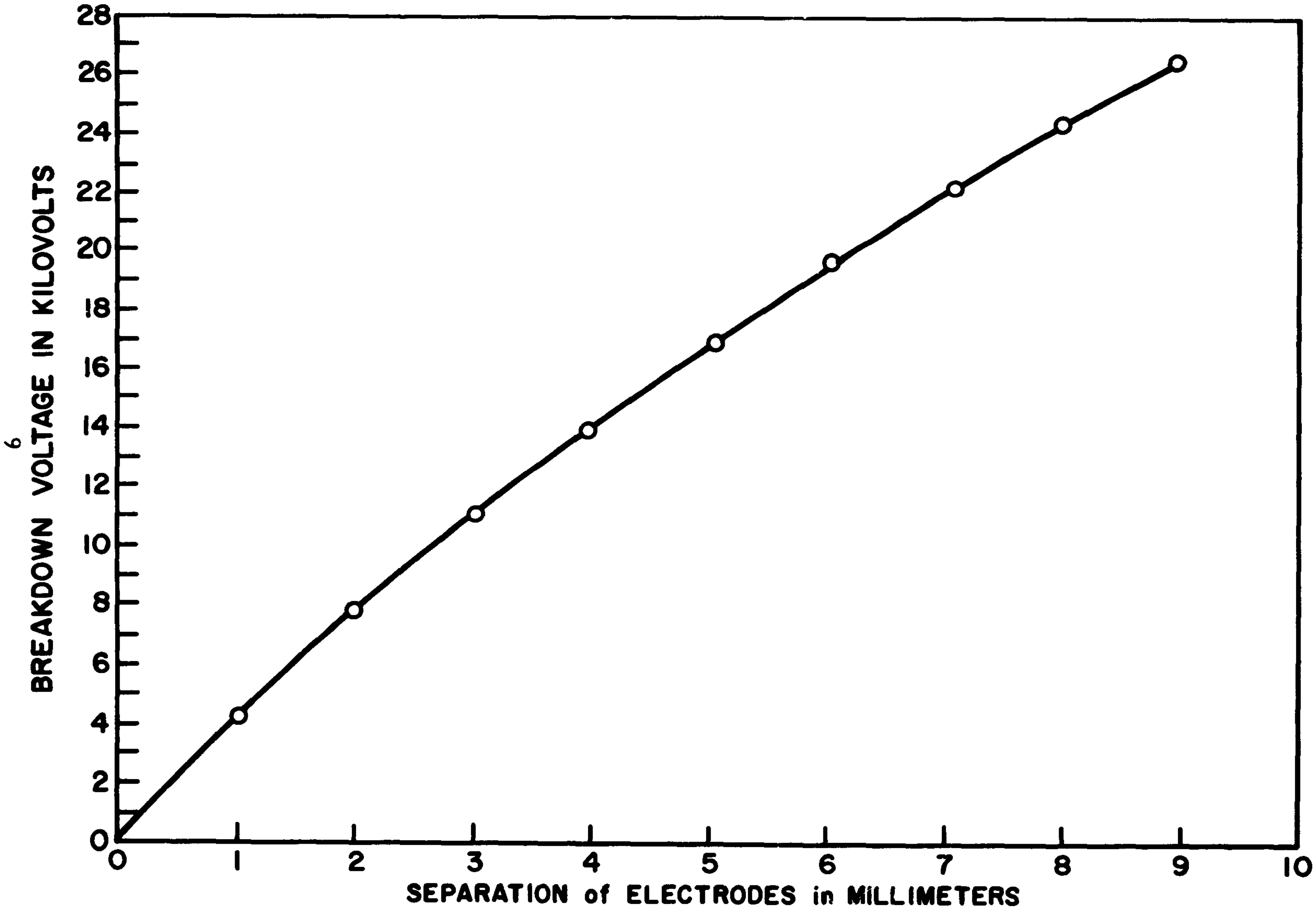

FIGURE 2. SPONTANEOUS BREAKDOWN VERSUS GAP WIDTH

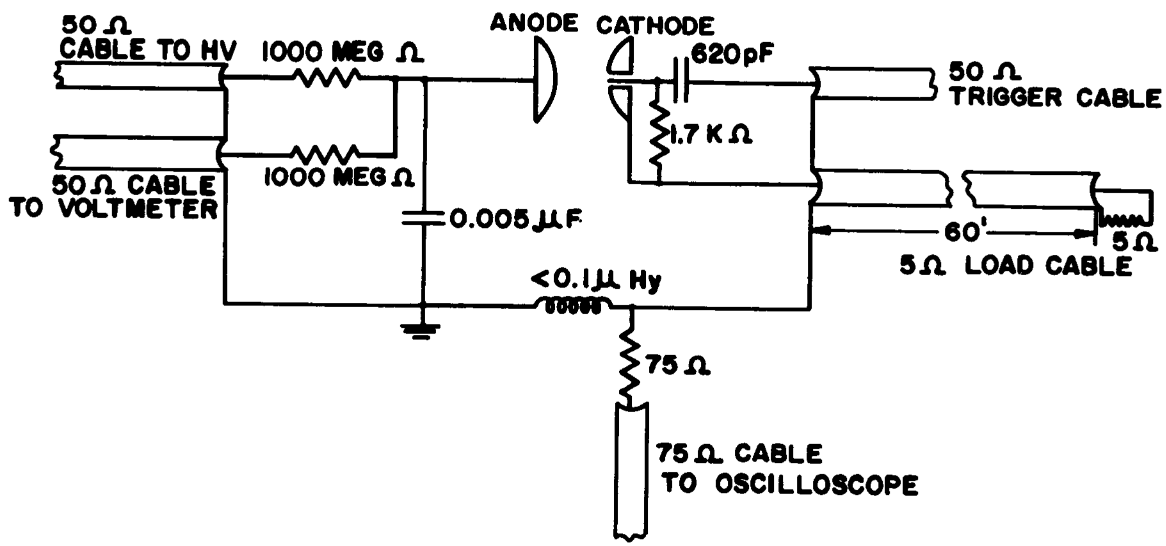

FIGURE 3. EQUIVALENT CIRCUIT FOR MEASURING SWITCHING TIME AND JITTER

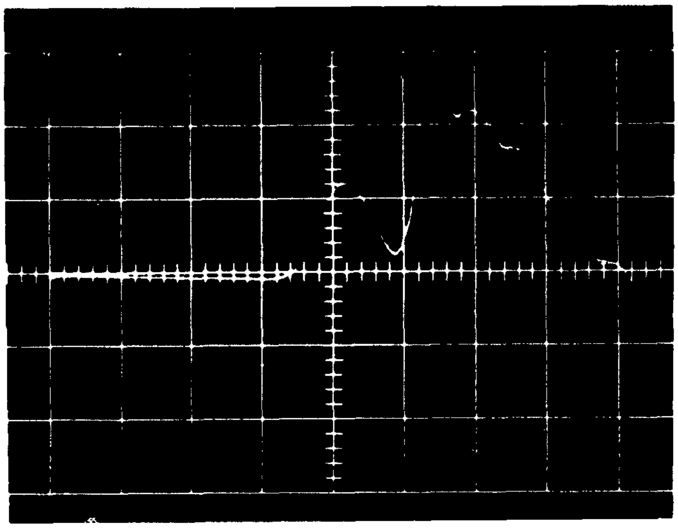

Figure 4. Voltage Across Inductor Upon Sponaneous Breakdown of 3 mm Gap. Time scale is 30 nsec/cm.

Figure 5. Photograph of Spontaneous Breakdown. Gap spacing is 3 mm and breakdown voltage is approximately 11 KV.

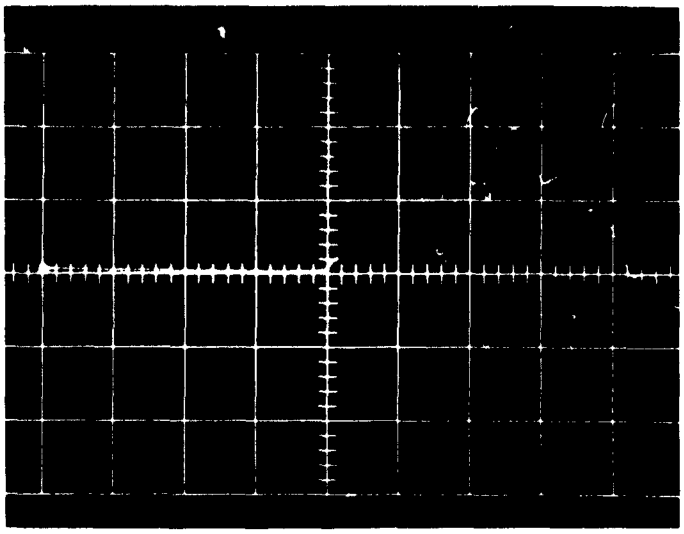

Figure 6. Voltage Across Inductor for Triggered Spark Breakdown. Trigger pulse is 20 KV. Gap spacing is 3 mm and the working voltage is 10.6 KV. Time scale is 20 nsec. cm.

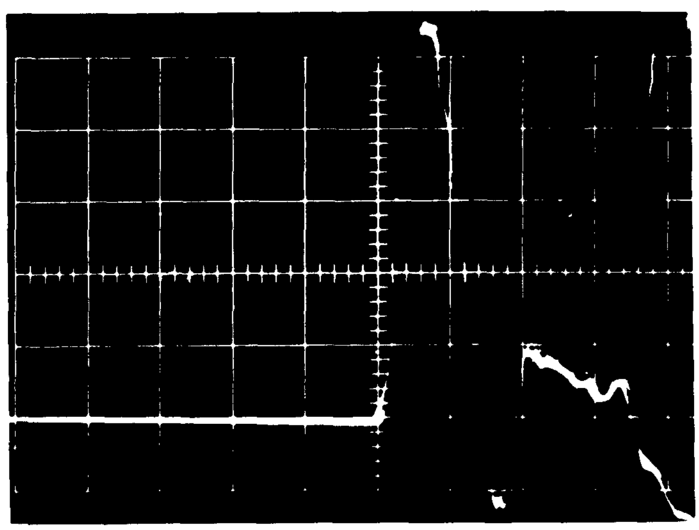

Figure 7. Voltage Across Inductor for 10 Triggered Discharges. Trigger pulse is 30 KV. Gap spacing is 3 mm and the working voltage is 9 KV. Time scale is 20 nsec/cm.

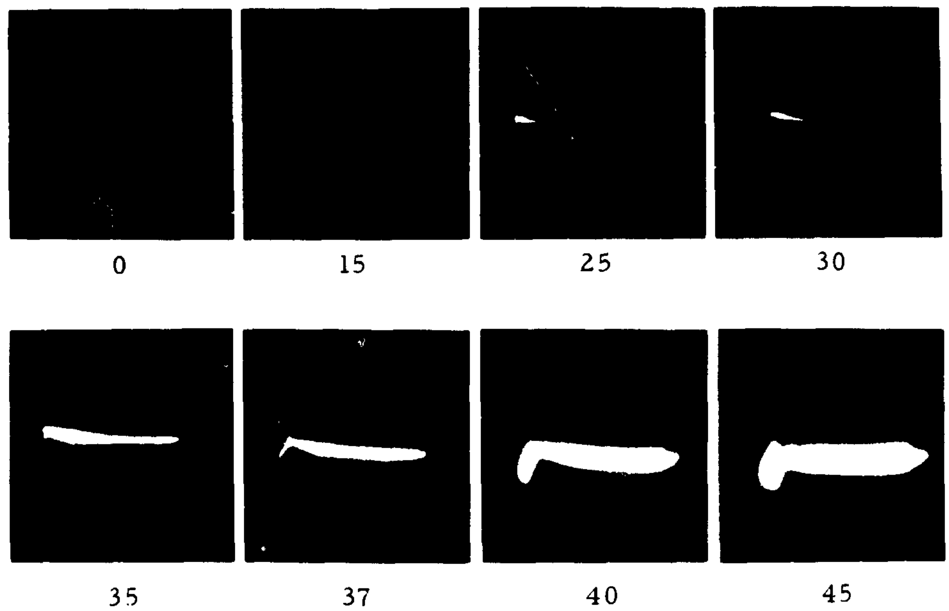

Figure 8. Time Sequence Photographs of T$_{r}$iggered Breakdown for "Fast" Mode. Kerr cell opening is 5 nanoseconds in each picture. Delay times are given in nanoseconds.

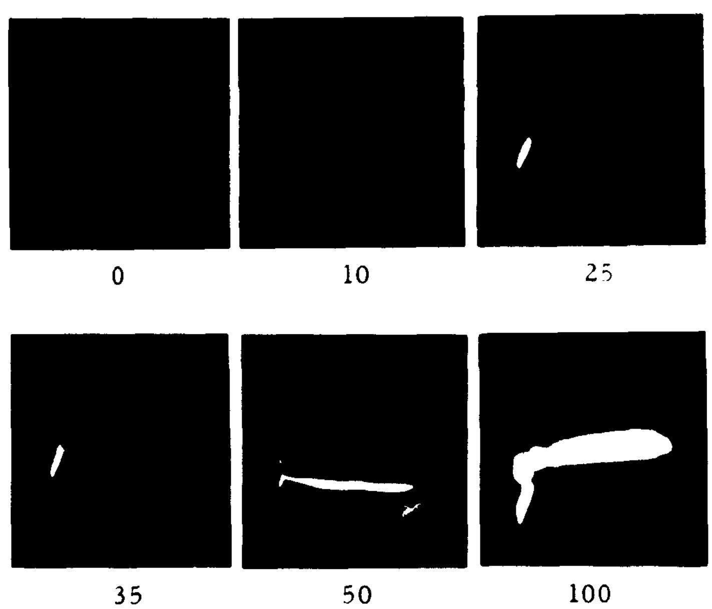

Figure 9. Time Sequence Photographs of Triggered Breakdown for "Slow" Mode. Kerr cell opening time is 5 nanoseconds in each picture. Delay times are given in nanoseconds.